The Cosmogony of Super-Massive Black Holes

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1 Introduction and Motivation

Two recently found properties of (super-massive) black holes (SMBHs) in the centers of active galaxies shed new light on their formation and growth:

- The luminosities of the quasars with the largest redshifts indicate that central BH masses of $> 10^9\,\mathrm{M}_\odot$ were already present when the Universe was less than 10^9 years old (Barth et al. 2003). These masses are lower limits as they are based on the assumption that the BHs accrete at their Eddington limit. There is no indication that the (majority of the) sample of highest-redshift-quasar luminosities is afflicted by amplification by gravitational lensing (White et al. 2005).
- Surveys in the X-ray regime (Hasinger et al. 2005) and in the optical/UV regime (Wolf et al. 2003) show a strong luminosity dependence of the redshift at which the active galactic nuclei (AGN) space density peaks: The lower the AGN luminosity, i.e., the smaller the BH mass, the later in the evolution of the Universe the co-moving space density of these AGN peaks. In other words, it takes BHs of a lower *final* mass longer to reach that mass than BHs of a larger final mass. This is also supported by a comparison of the local and the derived accretion mass function of SMBHs (Shankar et al. 2004).

In this contribution we report results of a project investigating the growth of SMBHs by disk accretion. We find that both above-mentioned phenomena can be explained in the framework of such a model.

2 Black Hole Formation and Growth in Galactic Centers

Our model involves two basic processes, namely: (a) galaxy mergers resulting in aggregation of material into a self-gravitating disk around the galactic

center (GC); and (b) subsequent disk accretion into a central BH. The issue in the past has been whether enough disk material could be accreted in the available time, a problem that has become steadily more acute as increasingly luminous quasars have been found at great redshifts.

In regard to (a), we envisage that the interaction between two (gas rich) galaxies leads to the rapid formation of a circum-nuclear gaseous disk. This process is expected to occur on a dynamical time scale. The mass and spatial extent of this disk will depend on the mass and gas content of the interacting galaxies and on the impact parameters of the collision. The process will thus result in a range of disk masses and extents.

For our subsequent reasoning it is important to note that fairly early in the evolution of the Universe ($z > 1.5 \cdots 3$) massive galaxies were already in place (Chen & Marzke 2004, Glazebroke et al. 2004, van Dokkum & Ellis 2003). Moreover, there is mounting evidence (e.g., Dunlop et al. 2003, Sánchez et al. 2004) that interactions between and mergers of galaxies trigger nuclear activity (e.g., McLeod & Rieke 1994a&b, Bahcall et al. 1997, Canalizo & Stockton 2001, Sánchez et al. 2005, Sanders 2004).

Thus for a *major merger* the resulting gaseous disk mass may well contain $> 10^{10}\,\mathrm{M}_\odot$ within a few hundred parsecs of the GC. This basic process has been demonstrated by numerical simulation (e.g., Barnes 2002, Barnes & Hernquist 1996 & 1998, Iono, Yun, & Mihos 2004) and provides the essential initial conditions for our analysis. The resulting nuclear disk will, of course, be subject to viscous dissipation causing an inward flow of material towards the GC where it is potentially available for accretion into a BH. With the initial mass and radius parameters discussed above, such a disk must inevitably be self-gravitating, at least initially. In these circumstances, the disk accretion time scale and, hence, the growth times and limiting mass of the putative BH, depend on both the mass and extent of the initial disks.

We also note that, initially, the disk may provide mass to the BH at a rate higher than is allowed by the Eddington limit. Thus in such a case initially the BH growth rate is defined by the Eddington limit, with the rest of the material presumably driven from the system (or at least the proximity of the BH) by radiation pressure. The peak luminosity will occur roughly when the rate of supply of material from the disk equals the Eddington limit for the current BH mass (higher for higher accretion rate).

3 Evolution of Self-Gravitating Accretion Disks and the Growth of Black Hole Masses

We carried out numerical simulations modelling the evolution of initially self-gravitating accretion disks and the ensuing growth of the central BH. Our model disks are geometrically thin and rotationally symmetric, with the following modifications with respect to standard accretion disk models:

- We allow for a disk mass which is not necessarily small compared to the mass of the central BH, i.e., we do not assume a Keplerian rotation curve in the disk but solve Poisson's equation.
- We use the generalized viscosity prescription by Duschl et al. (2000; β-viscosity).
- We take the Eddington limit into account. Mass flow above the Eddington limit is assumed to be lost from the system.

Our numerical code is based on an explicit finite-difference scheme. For further details of the modelling, we refer the reader to an upcoming paper (Duschl & Strittmatter, *in prep.*)

3.1 A Reference Model

As a Reference Model, we define an accretion diks with the following set of parameters:

- Inner radius of the disk: $s_\mathrm{i} = 10^{16.5}\,\mathrm{cm}$
- Outer radius of the disk: $s_\mathrm{o} = 10^{20.5}\,\mathrm{cm} \approx 10^2\,\mathrm{pc}$
- Initial disk mass: $M_{\mathrm{d},0} = 10^{10}\,\mathrm{M}_\odot$
- Initial surface density distribution: $\Sigma_0\,(s) \propto s^{-1}$.
- Seed black hole mass: $M_{\mathrm{BH},0} = 10^6\,\mathrm{M}_\odot \ll M_{\mathrm{d},0}$
- Viscosity parameter: $\beta = 10^{-3}$.

3.2 The Evolution of the Reference Model

The evolution of the mass flow rate of the reference model is shown in the left panel of Fig. 1. The right panel shows the corresponding evolution of the BH mass. The zero-point of the time is the point at which, as a consequence of a galaxy-galaxy interaction, a massive nuclear accretion disk has been established. One can clearly discern two phases of the accretion process: From the beginning of the evolution to $t_\mathrm{Edd} \sim 2.7 \cdot 10^8$ years the evolution is dominated by the Eddington limit: The disk delivers mass at a larger rate (broken line; $\dot{M}_\mathrm{d}$) than the BH can accrete due to the Eddington limit (dash-dot-dotted line; $\dot{M}_\mathrm{Edd}$). For times $t < t_\mathrm{Edd}$ the growth rate of the BH, $\dot{M}_\mathrm{BH}$, is subject to the Eddington limit, i.e., $\dot{M}_\mathrm{BH}\,(t < t_\mathrm{Edd}) = \dot{M}_\mathrm{Edd}$. For $t > t_\mathrm{Edd}$, however, both the mass of the BH has become so large and the mass flow rate from the disk has dropped by so much that $\dot{M}_\mathrm{d}$ now has fallen below $\dot{M}_\mathrm{Edd}$ and all the mass delivered by the disk can be accreted: $\dot{M}_\mathrm{BH}\,(t > t_\mathrm{Edd}) = \dot{M}_\mathrm{d}$. For the following few 10^8 years the free accretion rate, however, is still large enough to make the BH grow at a fast rate. This is slowed down considerably only after another $\sim 3.5 \cdot 10^8$ years by when the accretion rate has fallen by approximately one and a half orders of magnitude. From now on the BH grows only slowly; it has almost reached its *final* mass of $2.1 \cdot 10^9\,\mathrm{M}_\odot$ (broken line in the right panel).

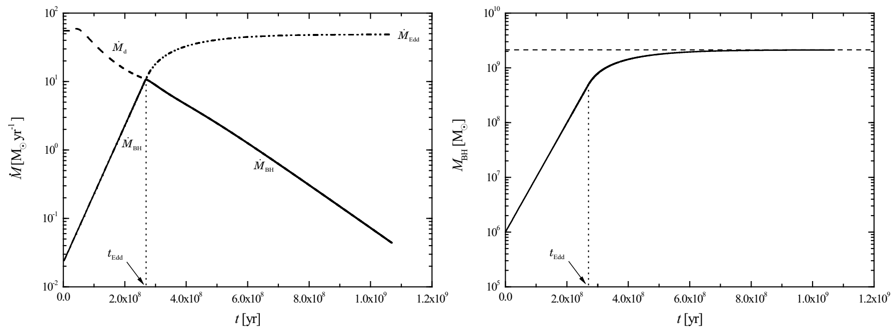

Fig. 1. The evolution of the mass flow rate (left panel) and the BH mass (right panel) for the reference model.

3.3 Variations of the Initial Physical Setup: The Black Hole Growth Time

As an example of the influence of the variation of the initial physical setup, we show in Fig. 2 the growth time scale $t_{0.5}$ of BHs where the initial disk mass and the inner disk radius have been changed, while all the other parameters of the reference model remained unaltered. $t_{0.5}$ is defined as the time at which the BH has reached half its final mass. In all our models, at this time the accretion rate, and thus the accretion luminosity have already fallen considerably below their maximum value. It is noteworthy that for BH masses in the realm of our GC, the growth times reach values comparable to the Hubble time.

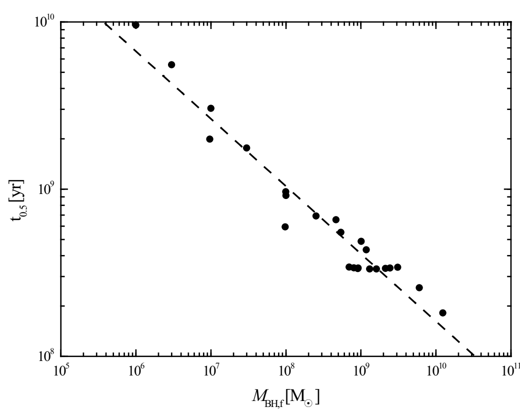

Fig. 2. The BH growth time scale $t_{0.5}$ as a function of the final BH mass M_{BH}.

4 Discussion and Outlook

Massive accretion disks seem to have the required properties to explain the observations described at the beginning of this contribution: The BH mass growth is quick enough to account for the inferred masses in the highest-redshift quasars, and the evolution time is an inverse function of the final BH mass[3]. We expect that the evolution of the Universe as a whole will even emphasize the latter effect: In the early Universe, galaxy mergers and collisions were much more frequent than they are in today's Universe making high initial disk masses more likely at higher redshifts. For a detailed comparison to the observed luminosity functions (e.g., Hasinger et al. 2005) this cosmological evolution of the initial conditoions has to be taken into account.

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[3]For a presentation of the entire set of model calculations and for a more exhausting discussion of their results, we refer the reader to an upcoming paper (Duschl & Strittmatter, *in prep.*).